Tunable Diode Laser (TDL) Development for Trace Gas Spectroscopy and Metrology Systems

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Abstract

The current status of tunable diode lasers (TDLs) for spectroscopy and metrology systems is reviewed. Space qualified single mode distributed feedback (DFB) strained layer InGaAs(P) lasers grown on InP substrates with emission wavelengths from 1.2 to 2.06 have been developed, for the first time, for planetary atmospheric studies. TDLs at the wavelengths of 1.37 μm, 1.43 μm, and 2.04 μm for the detection of water, carbon dioxide and their isotopes have been fabricated for implementation in the Mars Volatiles and Climate Surveyor (MVACS) instrument as part of Mars '98 flight. Several of the advanced scientific systems currently under development at JPL require high power, narrow linewidth, highly stable lasers. Monolithic strained multiquantum well (MQW) corrugation pitch modulated distributed feedback laser with 10s of milliwatts of optical output power and less than 100 KHz linewidth is currently under development.

I. Introduction

Many Molecular species have absorption bands in the 1-5 μm wavelength region where III-V diode lasers can operate. Single frequency diode lasers can be temperature or current tuned so that an output wavelength coincident with a specific gas-absorption line can be obtained. Detection techniques based on the modulation of laser current yield sensitivities for measuring one part per million absorbance or smaller. For many gases this sensitivity corresponds to detection of sub-parts-per-million (ppm) concentrations over path lengths of few meters [1]. Compatibility with fiberoptics makes this technique attractive for certain remote-sensing applications, where a single laser source might probe gas concentrations in different locations accessed by fiberoptics [2]. Their sensitivity, speed, and ability to quickly discriminate gases makes them ideal for life support applications. Based on their material system, semiconductor lasers can be divided in to two main groups of IV-VI (lead-salt) and III-V lasers. Lead-salt lasers with emission wavelengths in the 3 to 30 μm wavelength range have been widely used for spectroscopy applications. Though the lead-salt lasers can easily be tuned over a relatively large wavelength range by temperature or current tuning, temperatures far below 150°K are required for CW operation and the longer the emission wavelength of the laser the lower the operating temperature. Besides the low temperature requirement, the major problem with lead-salt lasers is their reliability due to poor quality of IV-VI epitaxial material and difficulty in device fabrication. In contrast to lead-salt lasers, III-V InGaAsP/InP lasers operate in the 1.1-2.1 μm wavelength range at room temperature with excellent performance and reliability. With their sensitivity, low power consumption, low mass, and compact size, instruments based on these near-infrared TDLs have been developed for numerous commercial applications. They are used in toxic gas monitoring (workplace detection or industrial site monitoring), for medical applications such as breath analysis, mine safety monitors (methane and carbon monoxide detection), monitoring of pollutants in stack gases, and on-line monitors of combustion or chemical processes. Considerable progress has also been made in the mid-IR semiconductor lasers based on III-V antimonide material system [3-10]. New types of lasers have been demonstrated, output power has been substantially increased and operating temperature has been extended.

We describe in this paper the current status of III-V based semiconductor lasers in the 1-5 μm wavelength range. Single mode distributed feedback (DFB) strained layer InGaAs(P) lasers grown on InP substrates with emission wavelengths from 1.2 to 2.06 μm is described in section II. The status of mid-IR semiconductor lasers is reviewed in section III with several applications of tunable diode lasers described in sections IV and V.

II. TDLs in the 1.2-2.06 μm Range

The mature technology of near-IR 1.3 and 1.55 μm InGaAsP/InP diode lasers for fiberoptic communication has been extended to fabricate lasers that emit anywhere in the wavelength range of 1.2-2.06 μm. The typical lasers developed are strained-layer multi-quantum well (MQW) structures epitaxially grown on InP substrates. In such lasers, simple resonators formed by cleaved facets on the ends of the laser cavity often allows oscillation in multiple longitudinal modes covering 2-5 nm wide spectral range and thus is not suitable for spectroscopy applications. Spectroscopic applications typically require single wavelength operation with some degree of tunability. Highly-stable single-longitudinal-mode operation may be met by a distributed feedback (DFB) or distributed Bragg reflector (DBR) laser cavity. Both types of devices require the incorporation of a submicron lithographically defined grating buried within the laser structure which is accomplished using state-of-the-art fabrication and epitaxial techniques.

Compressively strained InGaAs quantum well structures on InP substrates have been used for the development of semiconductor lasers operating beyond 1.65 μm. In general, the InGaAs material wavelength increases with increased In composition and decreases under compressive strain and due to quantum size effects.

We have previously reported the room temperature operation of InGaAs/InP quantum well lasers at wavelengths as long as 2.06 μm [12-13]. In general, to obtain low threshold current lasers, the confinement energy of the quantum well must be large enough to prevent carrier overflow.

The light versus current characteristics of a typical 1 mm long laser under continuous operation (CW) at several temperatures is shown in Figure 1.

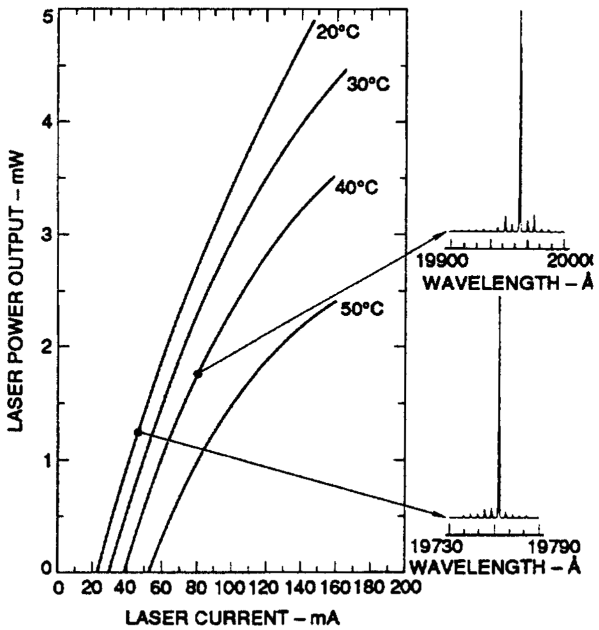

Fig. 1. Continuous light output against current for a ridge waveguide laser at ~2.0 μm at several temperatures.

Attempts to increase the emission wavelength of InGaAs/InP quantum well lasers beyond 2.08 μm resulted in poor quality crystal growth with no luminescence emission from the wafers. It has been concluded experimentally that 2.06-2.07 μm is the longest wavelength that reliable InGaAs/InP quantum well lasers could be fabricated using the present growth and fabrication techniques. Reliable DFB lasers at wavelength of 2.0465 μm have been fabricated and used for the detection of the CO2 isotopes.

III. Mid-IR Semiconductor Lasers

The III-V semiconductor lasers designed for mid-IR operation use various alloys and/or structures to achieve lasing. They include antimonide (Sb)-based type I and type II structures as well as InP- and Sb-based quantum cascade structures. A primary limitation in the development of high temperature type-I lasers is that the non-radiative Auger recombination process which makes it increasingly difficult to achieve a population inversion at high temperatures when the bandgap is small.

In contrast to type-I structures, calculations have predicted that Auger losses can be significantly suppressed in type-II superlattices and quantum wells. Type-II lasers employing InGaSb/InAs superlattices have been demonstrated. An electrically pumped type-II MQW laser at 3.1 μm under pulsed conditions operated up to a temperature of 250 K [6]. A similar device employing AlSb barriers was optically pumped under pulsed conditions, and this device lased up to 285 K with a corresponding wavelength of 4 μm [7]. More recently, a type II superlattice laser with an operating wavelength of 5.2 μm was demonstrated to lase under pulsed optical excitation up to 185K [8]. However, while both electrically-pumped and optically-pumped type-II mid-IR lasers have been demonstrated, the results appear to yield high temperature Auger coefficients no better than values expected for bulk type-I structures with the same bandgap.

Although optimization of the laser structures and improvements in the epitaxial growth has gradually increased the operating temperature of semiconductor lasers in the 2-10 μm range, more research is necessary to achieve room temperature CW operation. Further more, for spectroscopy applications the lasers will need to operate in a single longitudinal mode which could be accomplished by integrating a ridge laser with DFB or DBR gratings or possibly by using an external fiber Bragg grating. Whatever the choice, much work is still to be done in fabricating these mid-IR single mode lasers.

IV. TDLs for Trace Gas Spectroscopy

The Mars Volatiles and Climate Surveyor (MVACS) shown in Figure 2, is an integrated payload for Mars

Surveyor Program (MSP) '98 lander mission. The payload consists of four major science instruments which include two cameras, a Meteorology package, and a Thermal and Evolved Gas Analyzer. The mast mounted Meteorology package includes pressure, wind, and temperature sensors, as well as a tunable diode laser sensor for accurately determining water vapor concentration of the surface atmosphere. The TDL sensor measures water vapor concentration by monitoring the level of absorption of a single vibration-rotation line within the 1.37 μm water vapor band. the laser wavelength is repetitively scanned over a very narrow spectral interval, which includes the absorption line of interest, by sweeping the laser current with the laser operating temperature held fixed. The output beam is injected into a multi-pass Herriot type cell where two concave mirrors spaced 20 cm apart reflect the laser beam back and forth multiple times between distinctive spots on the mirrors. In such configuration the laser will produce 50 passes between the mirror, providing 10 meter optical absorption path capable of detecting surface concentrations better than one part per million.

Fig. 2 The Artistic presentation of Mars Volatiles and Climate Surveyor (MVACS) mission, Paige et. al. , to be launched as part of Mars Surveyor program.

The Thermal and Evolved Gas Analyzer is designed to determine the concentrations of ices, adsorbed volatiles, and volatile bearing minerals in surface and subsurface samples acquired by the robotic arm also uses two tunable diode lasers at 1.37 μm and 2.04 μm. This is the first time that tunable diode lasers have been considered and will be used for planetary atmospheric studies.Gas monitoring systems using TDLs is a fast growing area with a large commercial potential [14]. As an example, modern power plants use NH3 to reduce NOx emission from combustion processes. Accurate measurements and fast response times i. e. in-situ measurements during ongoing process, are of great importance when power station has to fulfill environmental legislation and obtain cost efficiency. Other commercial applications of considerable interest are remote detection of methane and acetylene using the combination of TDLs and fiber optics.

V. TDLs for Metrology

Several of the advanced scientific systems currently under development at JPL require high power, narrow linewidth, highly stable lasers. All of the stellar interferometry missions, such as, for example, Space Interferometer Mission (SIM) and New Millenium Interferometer (NMI), require laser sources suitable for high precision interferometric metrology. Intereferometric metrology systems are used to form optical trusses for structure definition and stabilization and for measurement of the stellar interferometer baseline. The lasers need to be high-power, because, as is the case in SIM, a single laser will be feeding all of the numerous metrology systems on board and, in the case of NMI, measurements must be performed over kilometer distances with high optical losses. In addition, both of the above missions require lasers with narrow-linewidth. NMI requires a high coherence laser so that an interferometric measurement can be performed with 1-10 km pathlength differences between the spacecraft comprising the stellar interferometer. For example, a target range of 5 km translates into a 30KHz linewidth requirement in order to form interference fringes. SIM on the other hand does not require high-coherence laser, but places a very strict requirement on the frequency stability of the laser. This requirement can be achieved by locking the laser frequency to a stabilized reference cavity. Using an electrical feedback approch a center of the laser line is made to coincide with the passband of the cavity. However, it is difficult to define the centroid of the laser line to better than a certain fraction of that line's width. For that reason high frequency stability requirement translates directly into the narrow-linewidth requirement.

The choice of technology used to implement the metrology laser sources with above characteristics needs to take into account the ruggedness, reliability, size, weight, and power consumption requirements associated with space qualification and deployment on future small and inexpensive spacecraft. Due to the critical alignment of many optical components within the solid state laser systems currently under development, their stability and space qualification remains to be a very challenging task. Semiconductor lasers are by far the simplest, cheapest and most reliable type of lasers available to date. This point is underscored by the fact that most of other compact laser source, e.g. Nd:YAG, are themselves pumped by semiconductor lasers. The recent advancements and impressive results achieved on the performance of semiconductor lasers in the past few years makes them a very reliable, efficient, and extremely low weight alternative laser source for meterology applications. Typical distributed feedback semiconductor lasers currently in use for telecommunication systems furnish a single wavelength with typical linewidth of few tens of MHz which is extremely wide and thus unacceptable for many of the advanced meterology systems. The spectral width of the semiconductor laser always becomes narrower as the output power is increased. In standard DFB lasers as the optical power increases the single-mode stability degrades and spectral width sharply widens mostly due to the spatial hole burning effect. For ultra-narrow linewidth operation of semiconductor lasers, it is essential to suppress the spatial hole burning effect at high output powers. A unique version of the distributed feedback structure namely the corrugation pitch modulated (CPM) structure is being developed. In CPM laser the grating pitch along the cavity of the semiconductor lasers is modulated to maintain a uniform profile of the light intensity along the laser cavity at very high electrical pumping levels. the uniform light intensity along the cavity results in reducing the spatial hole burning effect and hence significantly narrowing the linewidth of the semiconductor lasers, less than 20 KHz, at high output power.

Summary

The mature technology of near-IR 1.3 and 1.55 μm InGaAsP/InP diode lasers for fiberoptic communications has been extended to fabricate lasers that emit anywhere in the wavelength range of 1.1-2.06 μm. TDLs at the wavelengths of 1.37 μm, 1.43 μm, and 2.04 μm for the detection of water, carbon dioxide and their isotopes, respectively, have been fabricated for planetary applications. Considerable progress has been made in the performance of Sb-based mid-IR semiconductor lasers in terms of maximum operating temperature and output power for emission in the 2-5 μm wavelength range. Although optimization of the laser structures and improvements in the epitaxial growth has gradually increased the operating temperature of semiconductor lasers, more research is necessary to achieve room temperature CW operation in single longitudinal mode for these lasers to be suitable for spectroscopy applications.

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